Potential of Thermal Conditioning of Exhaust Gas for Stable Diesel Nano-Particle Measurement

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1. Introduction

Usually diesel nano-particles are classified into nuclei mode and accumulation mode particles. Particles less than 50 nm diameter are called as the nuclei-mode particles and particles larger than 100 nm diameter are called as the accumulation mode particles [1~2]. It is reported that the mass of nuclei-mode particles is almost negligible even particle number is very high. Therefore methods alternative to the conventional mass based one such as counting particle number is attracting much interest recently.

It is thought that human body reacts significantly against diesel nano-particles; especially the small size nuclei-mode particles are more dangerous than the accumulation mode particles. Particles larger than 2.5 μm can easily be trapped into the upper airways of the respiratory system. But particles smaller than 2.5 μm can easily penetrate deep into the lower airways and causes respiratory disease, followed by cardiovascular diseases for long time contamination. Therefore modification of the mass based present PM regulations received much attention globally. However diesel nano-particles are very unstable, especially the nuclei mode particles are significantly influenced by the circumferential conditions such as temperature, humidity, and residence time. Stable measurement of nano-particles with high accuracy is the most important pre-condition for regulation. As a part of stable measurement of nano-particles the GRPE/PMP Research Council of the United Nation has proposed "Thermo-Conditioner" [3]. The prime objective of thermo-conditioner is to vaporize the volatile fractions by re-heating the diluted gas to a certain temperature and cooling down again to room temperature. As the result measurement fluctuation due to volatile fractions can be avoided. However it is a newly developed device and performance of this device is yet to be understood sufficiently for many measuring parameters. Especially the characteristics of thermo-conditioned nano-particles are completely unknown. Therefore the prime objective of this study is to clarify the effect of thermo-conditioner on nano-particle characteristics under different conditions. Moreover stability in measurement was also confirmed depending on the characteristics of nano-particles.

2. Experimental System and Method

Figure 1 shows the schematic of the experimental system. The engine is an in-line six-cylinder direct injection diesel engine with common rail injection system having the bore of 114 mm and stroke of 130 mm and swept volume of 7.96 liter. The detail of engine specification is shown in Table 1. Exhaust gas was sampled from three different points; the point before silencer, the point before full dilution tunnel, and the point after full dilution tunnel. At the two upstream points thermal conditioning and hot dilution was performed with a Rotary-Disc Diluter (MD-19, Matter Engineering Ag) [4]. On the other hand at the point after dilution tunnel only thermal conditioning was done. SMPS (TSI, Model-3034) was used for analyzing the particle number concentration.

Figure 1: Schematic of the experimental system

The engine was operated at three different load conditions depending on the types and concentrations of nano-particles desired. The conditions are mentioned in detail in Table 2. It is generally thought that idling condition can produce a clear bi-modal distribution even at the engine out while the dilution process significantly influences the exhaust gas of low load condition [5]. Therefore idling and low load conditions have considered mainly in this study.

Figure 2 shows the rear view photograph of the Thermo-Conditioner. It consists of a main heating tube of which the temperature is controllable externally. Sample exhaust gas flows from the right side to left side. The heated sample gas is then flows through the heat exchanger for cooling to room temperature which then flows to sensors. Heating of the diluted gas results evaporation of the volatile fractions but immediate cooling to room temperature cannot re-condensate fully due to very low density of the diluted exhaust gas.

Figure 2: Photograph of Thermo-Conditioner

Table 1: Specifications of Test Engine

Engine Type	Six Cylinder DI-Diesel
Injection System	Common-rail
Bore x Stroke	114 mm x 130 mm
Swept Volume	7.96 Liter
Maximum Torque	745 N-m/1600rpm
Maximum Power	191kW/2700rpm
Emission Standard	Japan 1998

Table 2: Test Conditions

Idling	550 rpm x 0 N-m
Low-load	1200 rpm x 98 N-m
Medium-load	1620 rpm x 460 N-m
High Load	2160 rpm x 600 N-m
Thermo-Conditioner	25, 100, 200, 300, 400°C
Dilution temp. (DR)	25, 80, 150°C (50)

3. Results and Discussion

3.1 Effect of Sampling Points

Nano-particle number distributions at three different sampling points such as the point of before silencer (BS), the point before dilution tunnel (BDT) and the point after dilution tunnel (ADT) are shown in Figure 3. Before silencer hot dilution of exhaust gas at 150°C was also performed. The engine was operated at idling when both the nuclei mode and accumulation mode particles were generated. It shows that the distribution trend is almost the same at all sampling points. There is no significant difference in the concentration of accumulation mode particles when the sampling point changes. But the concentration of nuclei mode particles increases when the sampling point shifts to the downstream section. Shifting the sampling point to downstream section causes increases in the residence time of exhaust gas in low temperature dilution air. As the result some volatile fractions in the exhaust gas condense and may form nuclei mode particles during dilution. Comparing the results of with and without hot dilution at the point before silencer it is clear that the combustion-generated nuclei mode particles within the size range of 15~30 nm are significantly suppressed by hot dilution. It is thought that the particles formed in the dilution tunnel may be characteristically different from the combustion-generated nano-particles. Therefore a detail investigation is necessary to confirm the characteristics of both types of particles.

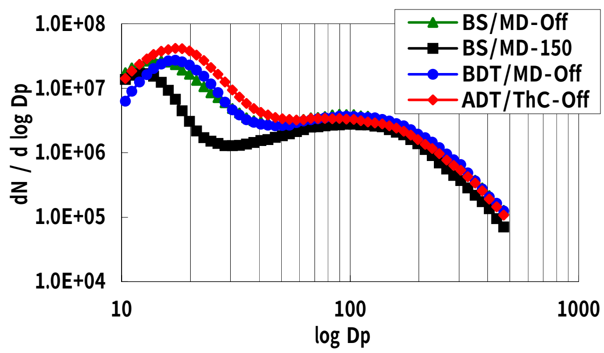

Fig. 3 Effect of sampling point on nano-particle number distribution (Idling: 550 rpm, 0 N-m)

Figure 4 shows the particle number distributions at different sampling points for low load condition. At this condition both the nuclei mode and accumulation mode particles are generated but it is thought that the dilution process significantly influences the exhaust gas. It is found from the graph that the concentration of accumulation mode particles does not change when the sampling point and the dilution process change. With hot dilution at the points before silencer and before dilution tunnel and with thermo-conditioning (ThC-300) at the point after dilution tunnel there were no significant emission of nuclei-mode particles within the size range of 15~30 nm. Only the concentration of nuclei mode particles less than 10 nm in diameter increases slightly in the downstream sections and a new peak can be expected in this region though it is beyond the measurement limit of SMPS. However without heat treatment (Hot Dilution and Thermo-Conditioning) a significant number of nuclei-mode particles were detected at the point after dilution tunnel. Therefore it can be concluded that some volatile fractions in the exhaust gas condense and form nuclei mode particles during dilution in the dilution tunnel.

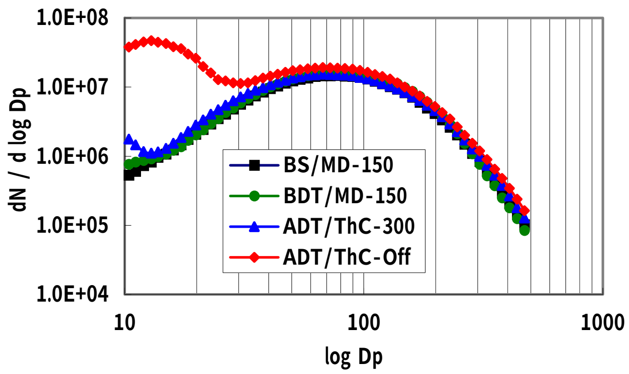

Fig. 4 Effect of sampling point on nano-particle number distribution (Low load: 1200 rpm, 98 N-m)

3.2 Effect of Dilution Temperature

The nano-particle number distributions at the point before silencer for different hot dilution temperatures are shown in Figure 5. The dilution temperature was varied by a rotary-disc type diluter keeping the dilution ratio constant (50). Variation in the dilution temperature logically corresponds to the variation of the condensation condition of the volatile fractions in exhaust gas. The engine was running at idling condition so that there was a bi-modal distribution at the engine out. Tests were done with and without thermal conditioning of exhaust gas.

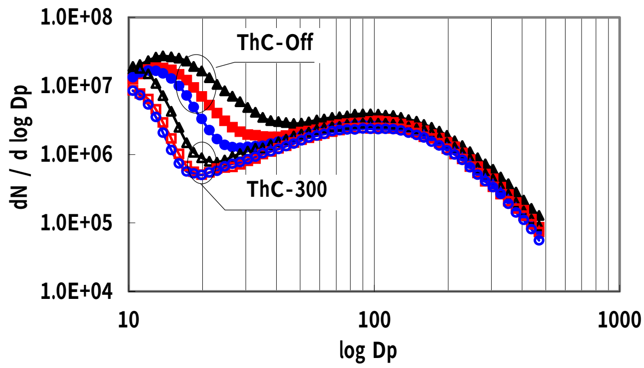

Fig. 5 Effect of dilution temperature on nano-particle number distribution (Idling: 550 rpm, 0 N-m), (MD: Rotary-Type Diluter Temperature °C)

The graph shows that hot dilution and thermal conditioning of exhaust gas has insignificant influences on the accumulation mode particles. Without thermo-conditioning (ThC-Off) concentration of nuclei mode particles within the range of 15~30 nm decreases significantly with increases in the hot dilution temperature. When thermo-conditioning is done at 300°C (ThC-300) it was found that concentration of nuclei mode particles decreases more but the influence of hot dilution temperature becomes insignificant between the dilution temperatures of 80°C and 150°C. However concentration of nuclei mode particles 10 nm in diameter or less shows no significant variations even with hot dilution and or thermo-conditioning.

3.3 Effect of Thermo-conditioning

Application of thermo-conditioner at the point after dilution tunnel is proposed by the GRPE/PMP, therefore variation in the thermo-conditioning temperature logically corresponds to the variation in the evaporation condition of volatile and semi volatile particles condensed during dilution in the full dilution tunnel. However in this study thermo-conditioner was used before and after dilution in order to investigate it's effect on both the combustion-generated nano-particles and the nano-particles formed in the dilution tunnel.

<u>Before Silencer</u>

Figure 6 shows the effect of thermo-conditioning temperature on nano-particle number distribution with hot dilution temperature of 150°C. Tests were done at idling condition and samples were taken from the point before silencer. At this point no cold dilution takes place, majority of the nuclei-mode particles are combustion generated with some volatile fractions condensed due to the drastic change in temperature across the exhaust valves [5]. Moreover as hot dilution is done at 150°C there is no water and most of the volatile particles may be HC having the boiling point sufficiently higher than 150°C.

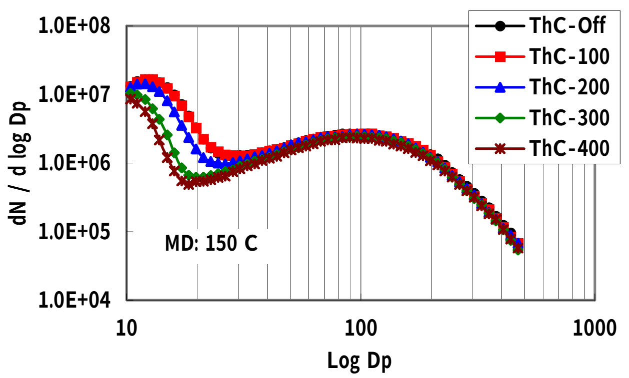

Fig. 6 Effect of Thermo-Conditioner on nano-particle number distribution at a point before silencer with hot dilution at 150°C (Idling: 550 rpm, 0 N-m)

The results show that there is no significant effect of thermo-conditioning on the concentration of accumulation mode particles. When the thermo-conditioning temperature is less than the hot dilution temperature (ThC-Off and ThC-100) there is no change in the concentration of nuclei-mode particles. Thermo-conditioning temperature higher than the hot dilution temperature (ThC-200~300) shows slight decreases in the concentration of nuclei-mode particles. Especially the peak of nuclei mode particle distribution shifts to the smaller size region. Thermo-conditioning temperature up to 300°C offers significant improvement but further increase in thermo-conditioning temperature does not offer significant improvement. From this result it is thought that thermo-conditioning at 300°C is sufficient for stabilizing the combustion generated nano-particles.

<u>After Dilution Tunnel</u>

Figure 7 shows the effect of thermo-conditioning temperature on nano-particle distribution at the point after dilution tunnel. The engine was operated at idling condition. Therefore the nuclei mode particles in this graph include both combustion-generated particles and particles formed in the dilution tunnel due to cold dilution. No hot dilution was performed in this case. The results show that without thermo-conditioning and thermo-conditioning at 100°C the concentration of nuclei mode particles within the size range of 15~30 nm is very high. As the thermo-conditioning temperature increases the peak shifts to the left and the concentration decreases. However thermo-conditioning temperature over 300°C shows no more suppression of nuclei-mode particles. Therefore thermo-conditioning temperature of 300°C was considered to be sufficient for stabilizing the nano-particles formed in the dilution tunnel. The concentration of nuclei-mode particles having 10 nm diameters or less does not change. The accumulation mode particles experience no significant influences within this thermo-conditioning temperature range.

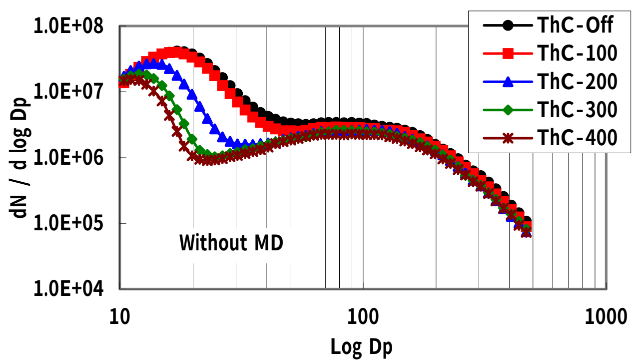

Fig. 7 Effect of Thermo-Conditioner on nano-particle number distribution at a point after full dilution tunnel without hot dilution (Idling: 550 rpm, 0 N-m)

The same test was performed at low load condition and the results are shown in Figure 8. It shows that without thermo-conditioning there is significant number concentration of nuclei mode particles within the size range of 10~30 nm. However it is suppressed significantly when thermo-conditioning is done at 100°C. Therefore it is thought that most of the nuclei mode particles in this graph are formed in the dilution tunnel due to condensation of water by cold dilution. Further increases in the thermo-conditioning temperature show decreases in the concentration of nuclei mode particles due to evaporation of the volatile fractions (HC). The nuclei mode particles almost disappear and concentration becomes saturated at the thermo-conditioning temperature of 300°C. Therefore it is thought that thermo-conditioning can suppress almost all the nuclei mode particles formed in the dilution tunnel due to cold dilution.

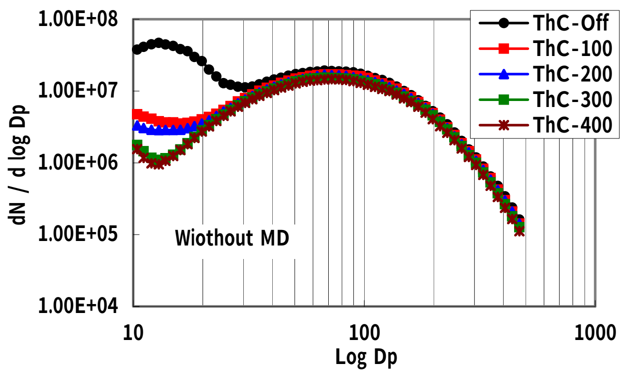

Fig. 8 Effect of Thermo-Conditioner on nano-particle at a point after full dilution tunnel without hot dilution (Low Load: 1200 rpm, 98 N-m)

3.4 Hypothetical Model for Nano-particles

Based on the experimental results a hypothetical model for diesel nano-particle has been proposed in this study. According to this model the nano-particles are classified into three major groups. The model is schematically represented in Figure 9.

Group-1: D_m= 10 nm (5 nm < D < 20 nm)

Particles within the size range of 5~20 nm and a distribution peak at 10 nm are included in this group. Particles in this group are relatively stable and are not affected by the thermo-conditioning temperature even up to 400°C. Therefore assumed to be core of nuclei particles which may be metallic ash or carbon or heavy HC having the boiling point over 400°C.

Group-2: D_m= 25 nm (10 nm < D < 40 nm)

Particles within the size range of 10~40 nm and a distribution peak at 25 nm are included in this group. Particles in this group are very unstable and are significantly affected by the thermo-conditioning and therefore assumed to be particles those may or may not consist of a solid core depending on the condition but always consist of some volatile fractions. The volatile fractions may be water condensed in the dilution tunnel due to cold dilution and molecular HC having the boiling point of less than 300°C.

Group-3: D_m= 100 nm (30 nm < D < 150 nm)

Particles within the size range of 30~150 nm and a distribution peak at 100 nm are included in this group. Particles in this group are solid particles such as soot or agglomerate of some solid soot. These cannot be affected by thermo-conditioning.The three groups of particles proposed in this hypothetical model do not contradict with the typical bi-modal distribution of diesel nano-particles. The second group has a tendency to merge with the first group or third group depending on the heat treatment and residence time when measured by conventional CPC or Electrometer. Therefore measurement of only 10 nm and 75 nm particles instead of measuring all the particles can give information about almost all the nano-particles. However a detail chemical analysis is necessary to understand the composition and structure of the nano-particles.

4. Conclusions

The potential of Thermo-Conditioner for stable measurement of nano-particle under different conditions have been investigated and the characteristics of thermo-conditioned particles have been clarified in this study. The following conclusions have been drawn:

1. The nuclei-mode particles within the size range of 15~30nm are significantly influenced by the thermal conditioning temperature while the accumulation mode particles having the diameter of about 100 nm experience no influence.
2. Thermal conditioning of exhaust gas at a temperature of over 300°C is sufficient for stable measurement. Hot dilution by a rotary disk type diluter followed by thermal conditioning showed better stability.
3. Thermo-conditioner can completely vaporize almost all the volatile fractions formed during the cold dilution process. But it fails to suppress all the nuclei-mode particles formed during in-cylinder combustion and sudden cooling across the exhaust valves.
4. A new hypothetical model for diesel nano-particles has been proposed depending on the characteristics found in this study.

5. References

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